

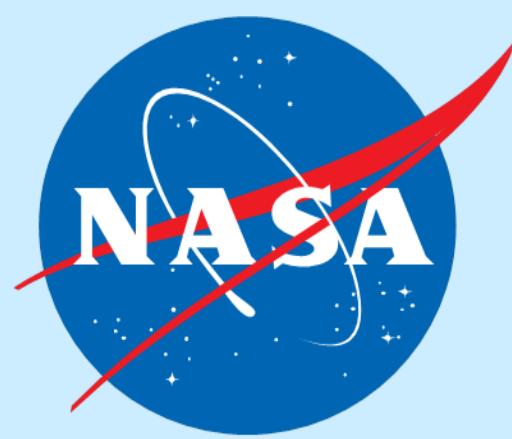
Implementation and Integration of a Finite Element Model into the Bone Remodeling Model to Characterize Skeletal Loading

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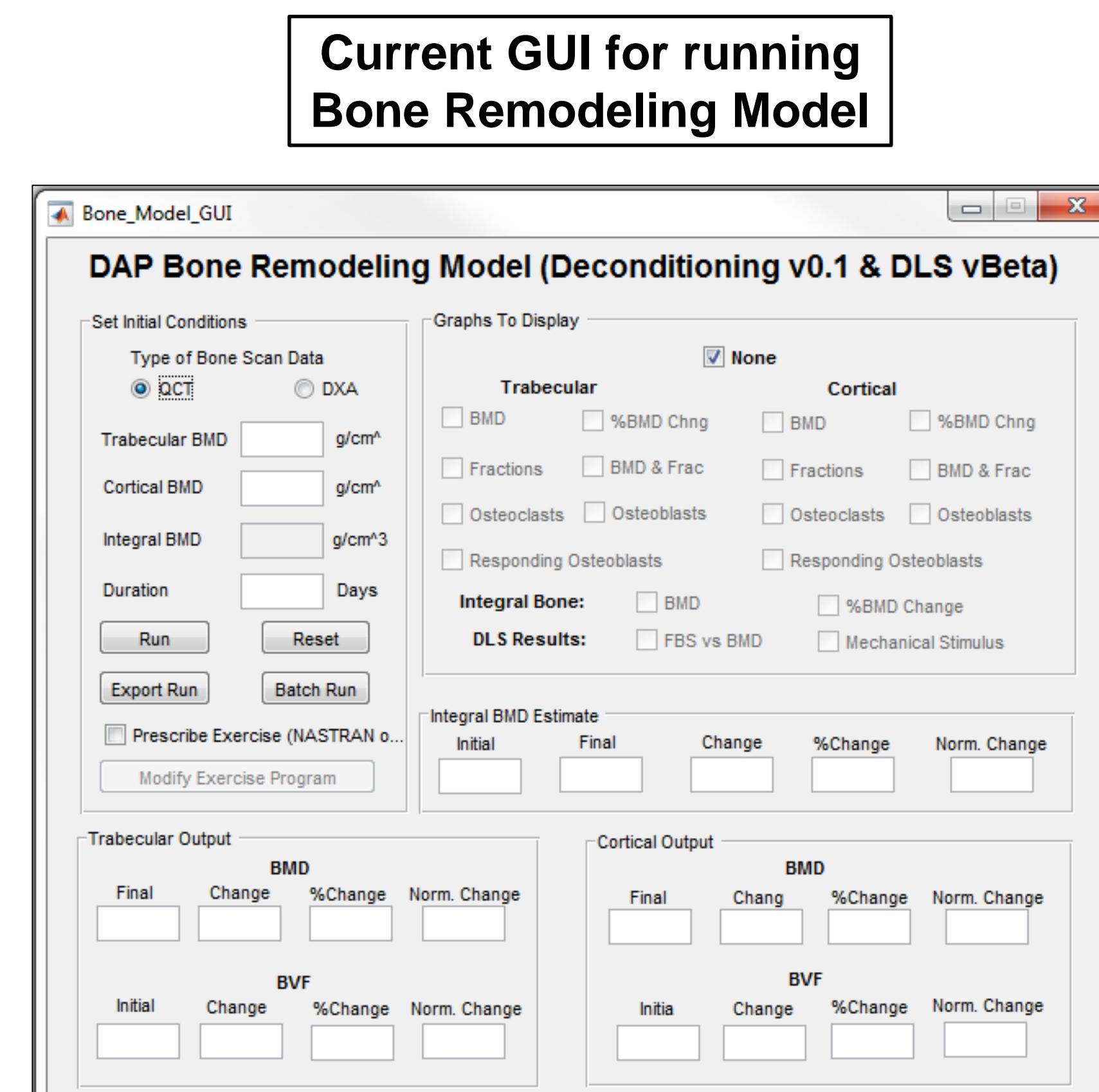
National Aeronautics and Space Administration



INTRODUCTION

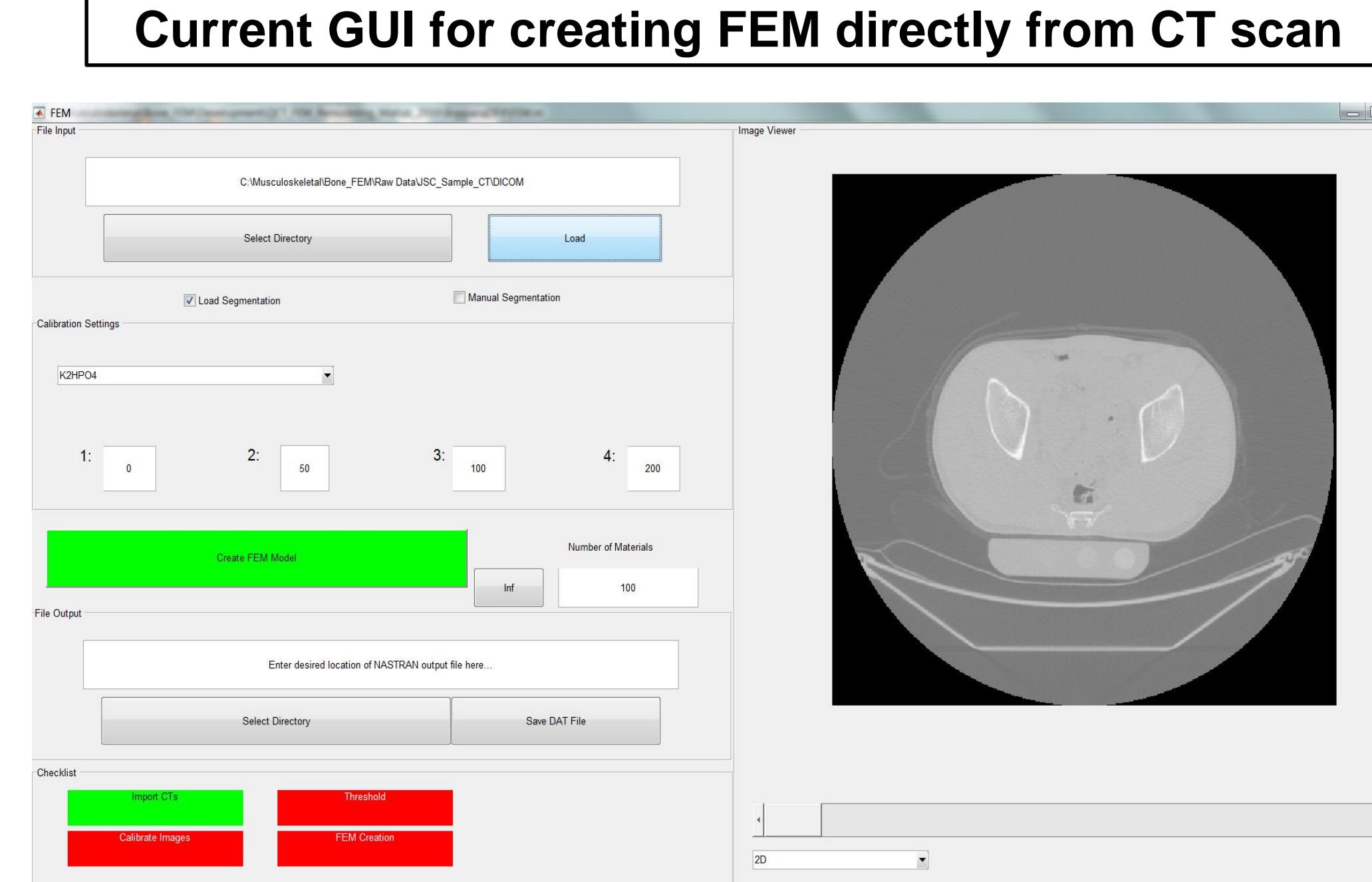
Background

- The Digital Astronaut project is developing a bone physiology model to predict changes in bone mineral density over the course of a space mission, by predicting bone loss due to exposure to a microgravity environment, and by predicting bone maintenance due to mechanical stimulus generated by exercise countermeasures. These predictions will be used to inform exercise device efficacy as well as develop exercise protocols that maintain healthy bone mineral density during long duration spaceflight missions.
- The mechanical stimulus sensed by the bone and the stresses that are applied to the bone are important factors for bone remodeling
- The stresses are dependent on the type of exercise and vary across the bone structure due to geometry
- One of the primary regions of concern for bone loss in spaceflight is the proximal femur.



New FEM Description

- An anonymous CT scan was supplied by JSC and an FEM was created directly from the scan
- The Dicom image stack is made of cubic voxels which can be converted to hexahedral elements using voxel size dimensions of 3mm
- Phantom Tube Calibration values are used to determine the bone density of selected voxels
- Modulus of elasticity is calculated using ash density and bone volume fraction relationships [2]
- Loads [3] are applied at the head and neck, but on groups of nodes which prevent the need to use a rigid element
- The base is constrained in all 6 DOF
- The CT FEM is generated using Matlab's Image Processing Toolbox. The bone remodeling model also uses the Matlab platform, therefore, information from the FEM can be easily passed to the Bone Remodeling code.



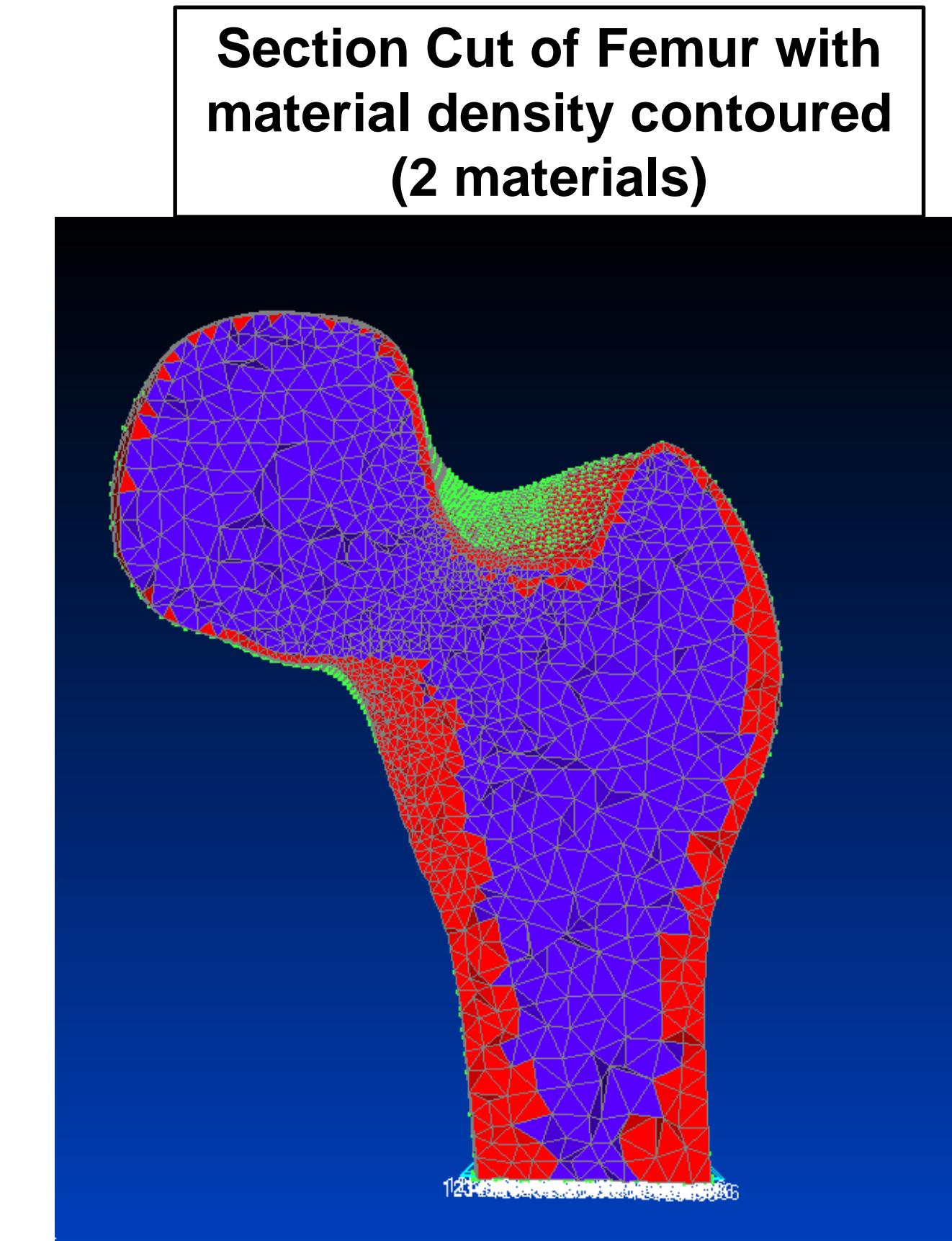
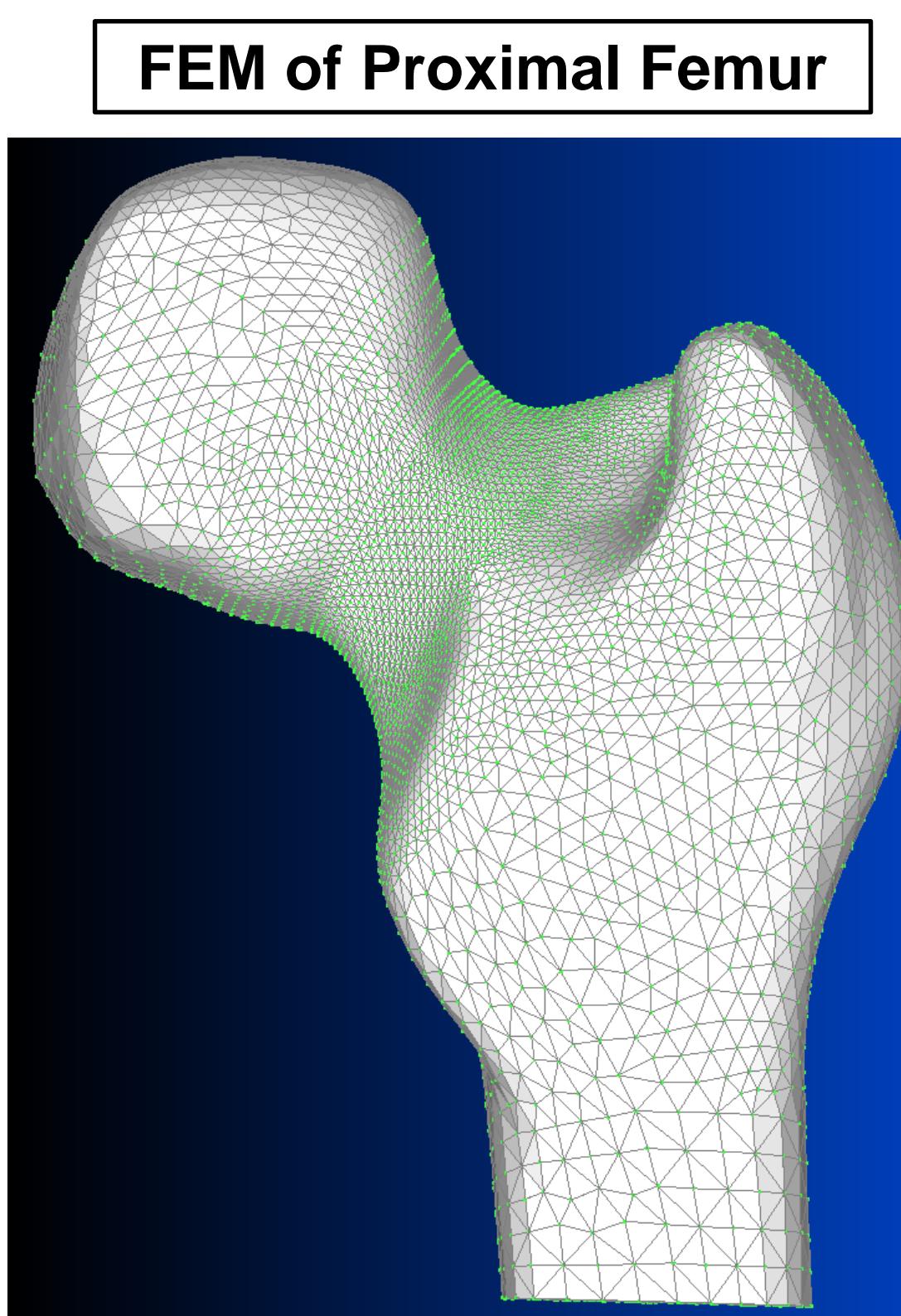
METHODS

Current FEM Description

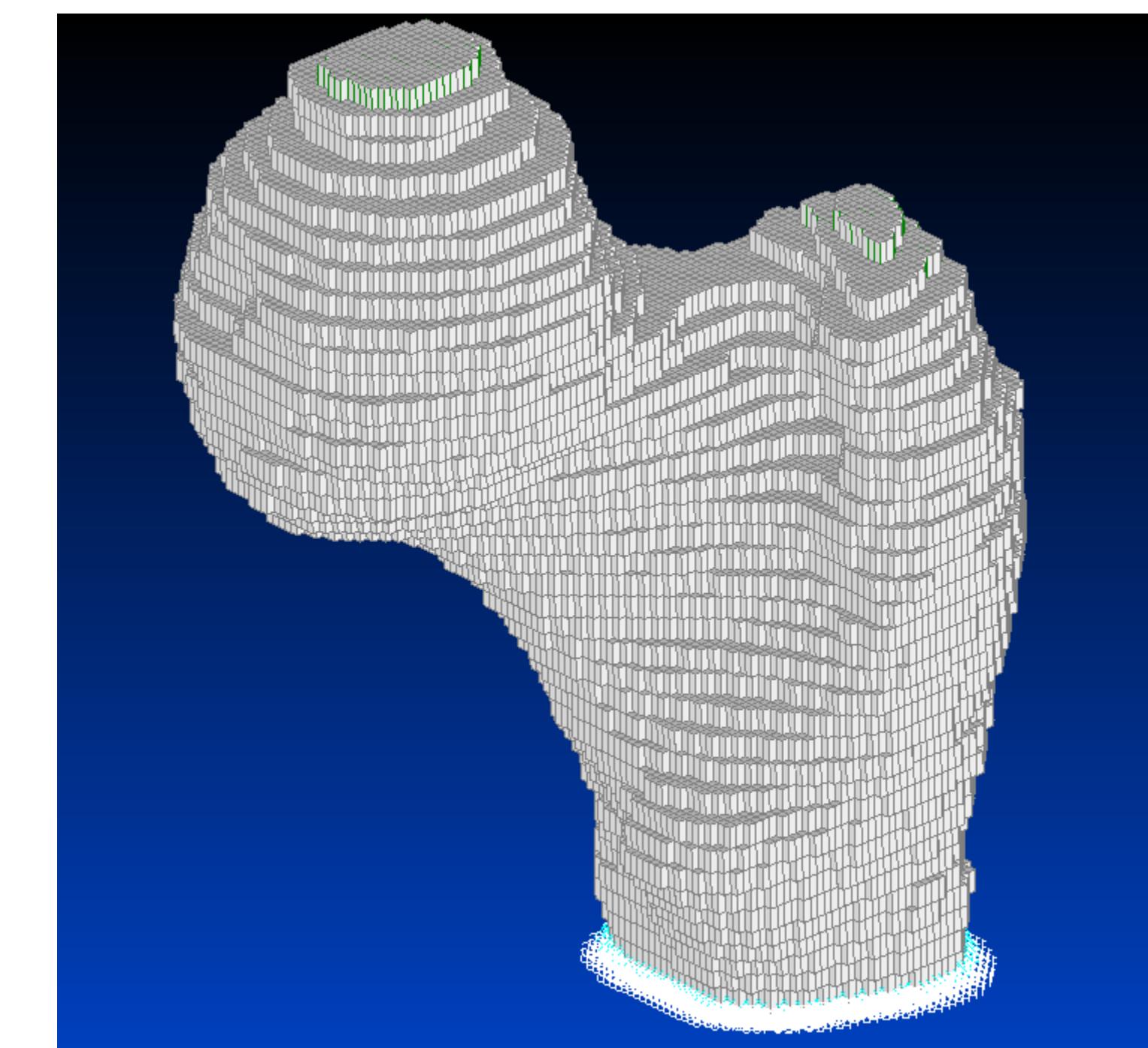
- The FEM is created from a CAD model created from an anonymous subject's CT hip scan [1]
- The CAD geometry allows for the use of automated meshing algorithms which use linear tetrahedral elements with higher mesh resolution on the surface and within the femoral neck
- Cortical and trabecular regions were qualitatively defined using manual selection methods.
- Loads are applied as single nodes at the center of the head and greater trochanter and distributed to the model surfaces via rigid elements
- The bottom surface is constrained for all 6 DOF
- While smooth on the outside, the FEM has limitations.

Limitations

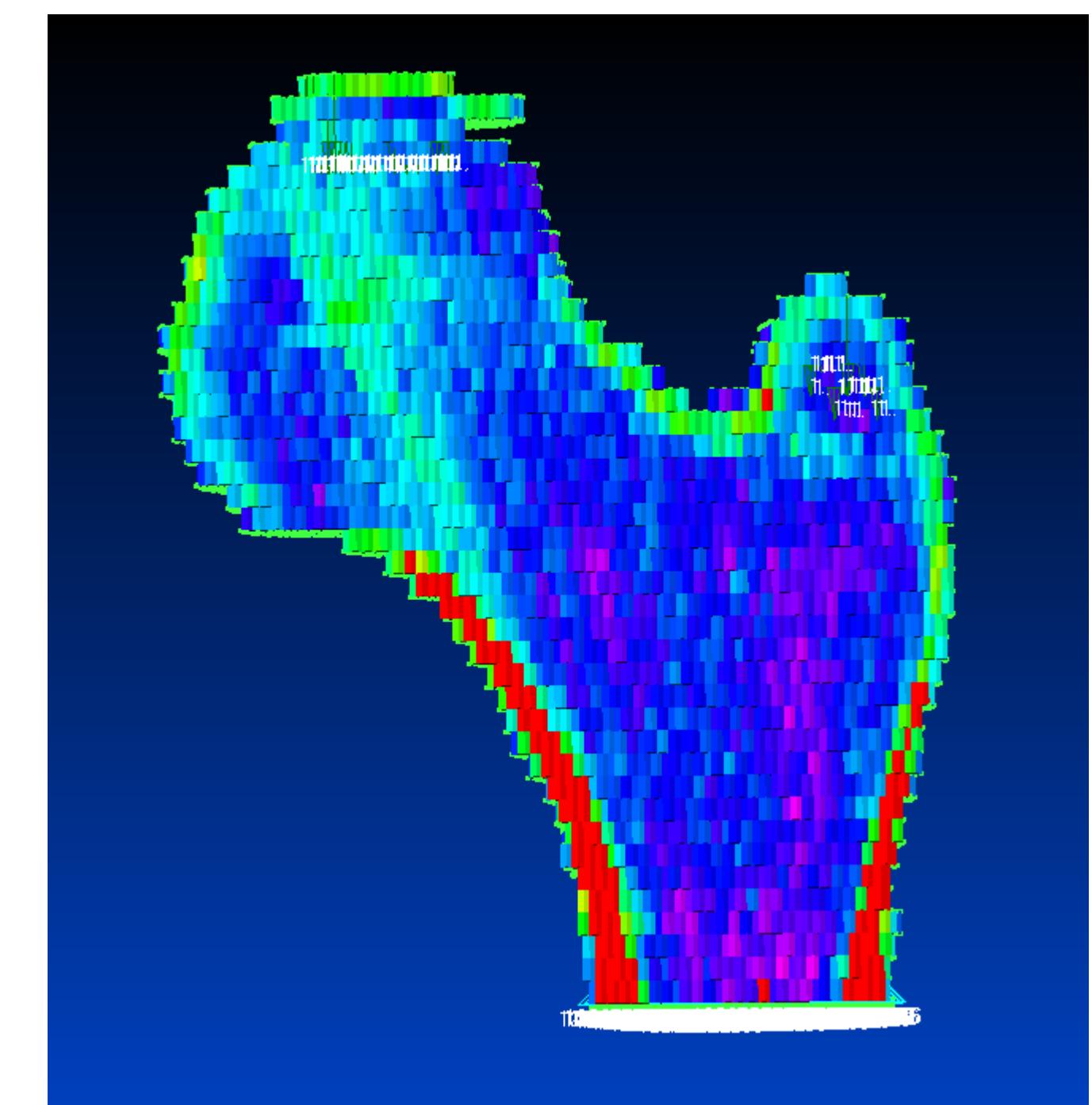
- The proximal femur model has only two material properties. This oversimplifies the femur and neglects the varying densities seen from CT scans
- The limitation of two material properties requires the consolidation of a single stress value per material, because the Bone Remodeling Model requires one stress value for each material modulus. The consolidation is handled by averaging the maximum principle stresses.
- The use of rigid elements make it easy to define loads, but also creates unrealistically high stresses at connecting nodes



FEM of Femur based on Voxels



Section Cut of Femur with material density contoured



FUTURE WORK

Enhancements to the FEM

- The Bone Remodeling Model has been restructured to perform the remodeling on an element by element basis, but still needs verification with former FEM versions
- Due to calibration issues, the new FEM, based directly on CT, has not been fully integrated at this point.
- Additional technical challenges are:
 - Appropriate load application for walking, running, and resistive exercises
 - Appropriate type of strain to use (current model assumes average of maximum principle stress)
 - Appropriate approximation or implementation of isotropic or anisotropic bone material properties
 - Appropriate averaging across the whole proximal femur
 - Ensure the Bone Remodeling Model is robust enough for the large variation of stresses throughout the bone

ACKNOWLEDGEMENTS

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[1] Werner, C. & Gorla, R.S.R., 2013. Int J Appl Mech, 18(3), pp.911–921.

[2] Chang, K.L. & Pennline, J.A., 2013. NASA/TM-2013-217842. Available online at: <http://ntrs.nasa.gov>

[3] Orthoload [http://www.orthoload.com/]

[4] Hazelwood, S. & Castillo, A., 2007. Int J Fatigue, 29(6), pp.1057–1064.

REFERENCES

PARTNERS

